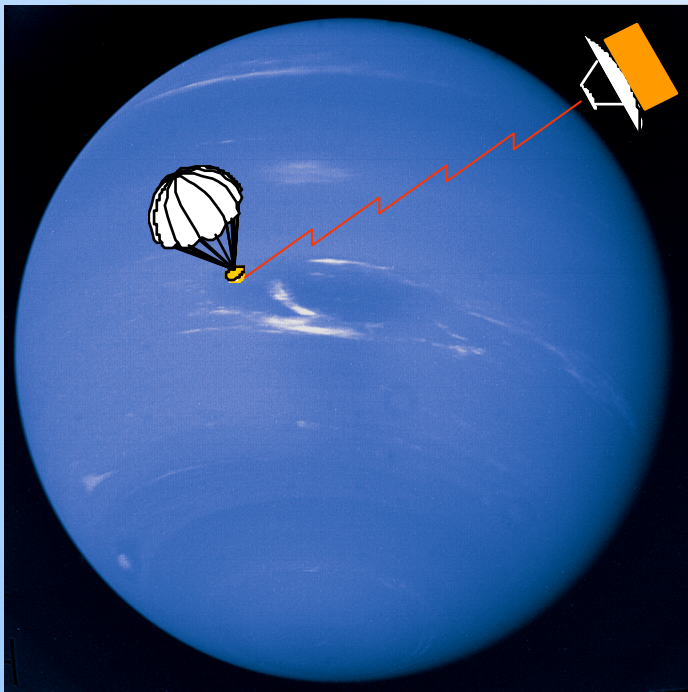




## Compositional Impact on Science & Engineering in Atmospheres



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IPPW-5 Short Course: Controlled Entry & Descent into Planetary Atmospheres  
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## Organization

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- Compositional effects on the atmosphere itself
- Compositional effects on science measurements
- Compositional effects on entry systems
- Compositional effects on descent systems
- Compositional effects on communications

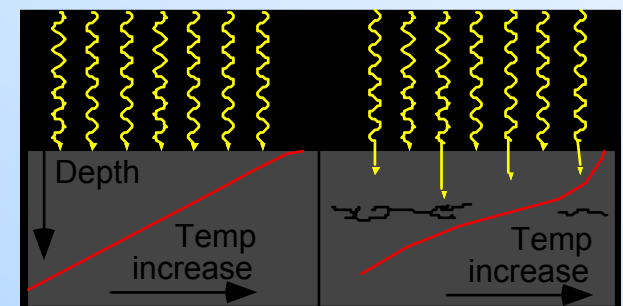
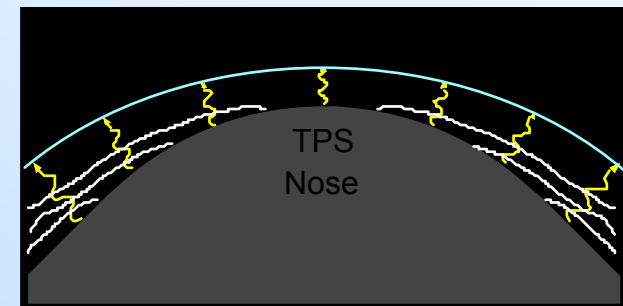
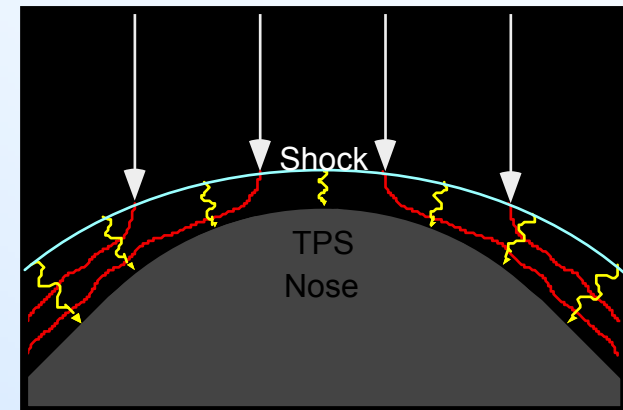
## Atmospheric Structure

- *Mean molecular mass*  $M$  is a parameter of fundamental importance
  - Strictly a function of composition
- *Atmospheric density*  $\rho$  is proportional to  $M$ 
  - All aerodynamic drag calculations depend on density:  $F_d = (C_d/2) A \rho V^2$
- *Scale height*  $H$  is a function of  $M$ 
  - Describes the local vertical gradient of pressure or density
    - ♦  $P(z) = P(z_0) \exp[-(z - z_0)/H]$  (“isothermal atmosphere”)
  - In real atmospheres  $H$  can vary from a few km to ~100 km
  - Values of  $H$  in the relevant density range are *critical* to entry trajectory design
- *Lapse rate* ( $dT/dz$ ) is important to structure and dynamics (esp. convection)
  - Multiple mechanisms for composition to affect lapse rate
    - ♦ Condensation and its latent heat (dry vs. wet adiabats)
    - ♦ Opacity to radiant energy
      - Sunlight going *downward*
      - Thermal emissions going *upward*
      - Greenhouse effect

$$H = \frac{RT}{Mg}$$

- Chemical aliasing
  - Can bias compositional measurements
    - ♦ One species' instrument response behaves like another
      - Instrument response can be misinterpreted, or...
      - One species' signal overwhelms the other's
  - Example: CO and N<sub>2</sub> in a low- to med-resolution mass spectrometer
- Condensation
  - Liquids or fine solids in instrument systems
    - ♦ Interfere with moving parts
    - ♦ Sampling systems
      - Example: H<sub>2</sub>SO<sub>4</sub> droplet plugging inlet to Pioneer Venus Large Probe mass spectrometer
  - Clouds, hazes
    - ♦ Interfere with imaging, other instruments requiring light propagation
    - ♦ Aerodynamics can generate local "clouds"
      - Effect commonly demonstrated above wings of aircraft in humid air
      - Can fool nephelometers

- Two heating mechanisms: *convective & radiative*
  - Air hitting the shock is compressed and heated tremendously; it moves (convects) into contact with the TPS and transfers the heat to the TPS
  - Air heated at the shock radiates at the TPS; the shock radiative spectrum is strongly influenced by composition of the air
    - ♦ Ex: Titan's atmosphere is mostly  $N_2$  but also contains  $CH_4$ : dissociated N and C form CN, a strong violet-UV radiator
  - Convective/radiative balance is a result of a complex interplay of Mach number and composition
- Two cooling mechanisms: *ablative & radiative*
  - Ablation: heated TPS material vaporizes and convects away with flowing air, carrying with it stored chemical energy, latent heat of sublimation, and thermal energy of higher temperature
  - Radiation: heated TPS material radiates energy away; but if the shock is strong, it may be opaque and absorb the outgoing radiation, reradiating some of it back at the TPS
- Radiative spectrum and heat deposition depth
  - In an ablative TPS, radiant heating at the surface yields a thermal profile that produces no interior cracking
  - Heat deposited at depth causes higher thermal gradients at depth and cracking (spalling), decreasing TPS effectiveness



Don't forget chemical reactions!

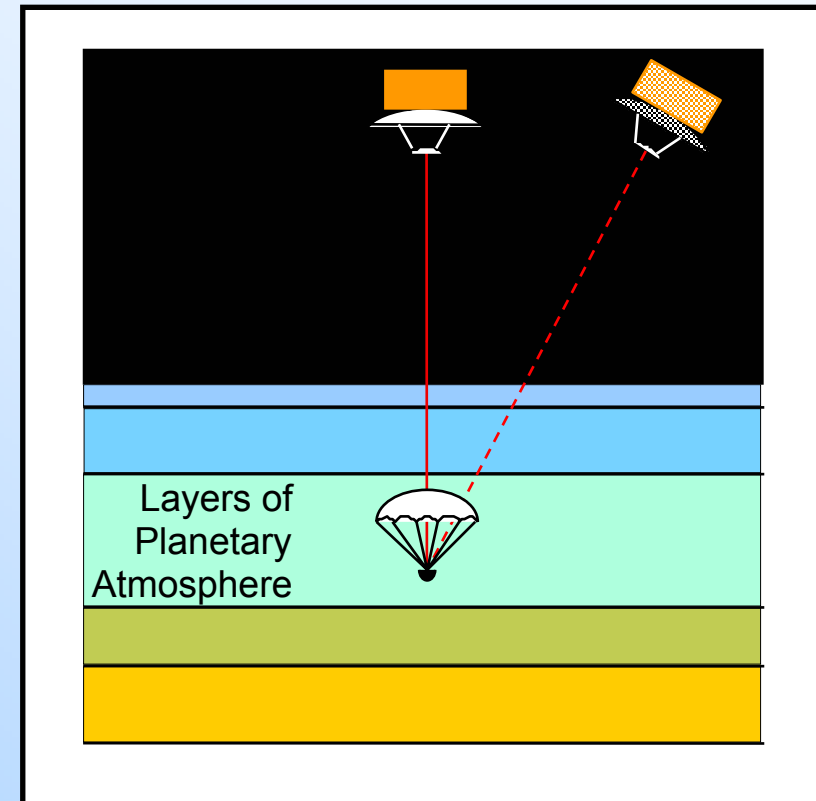
- Effectiveness of parachute systems
  - Drag produced per unit area is directly proportional to atmospheric density
- Condensation
  - Polar liquids (ex. water) or solutions (ex. ammonia in water) can coat surfaces
- Corrosion
  - Some atmospheric constituents can be quite corrosive
    - ♦ Example:  $\text{H}_2\text{SO}_4$  in Venus' atmosphere at altitudes of ~30-70 km
  - Components likely to be sensitive:
    - ♦ Parachute systems: canopy, lines, swivels
    - ♦ Exposed fine wires
    - ♦ Instrument sensors



## Effects on Communications

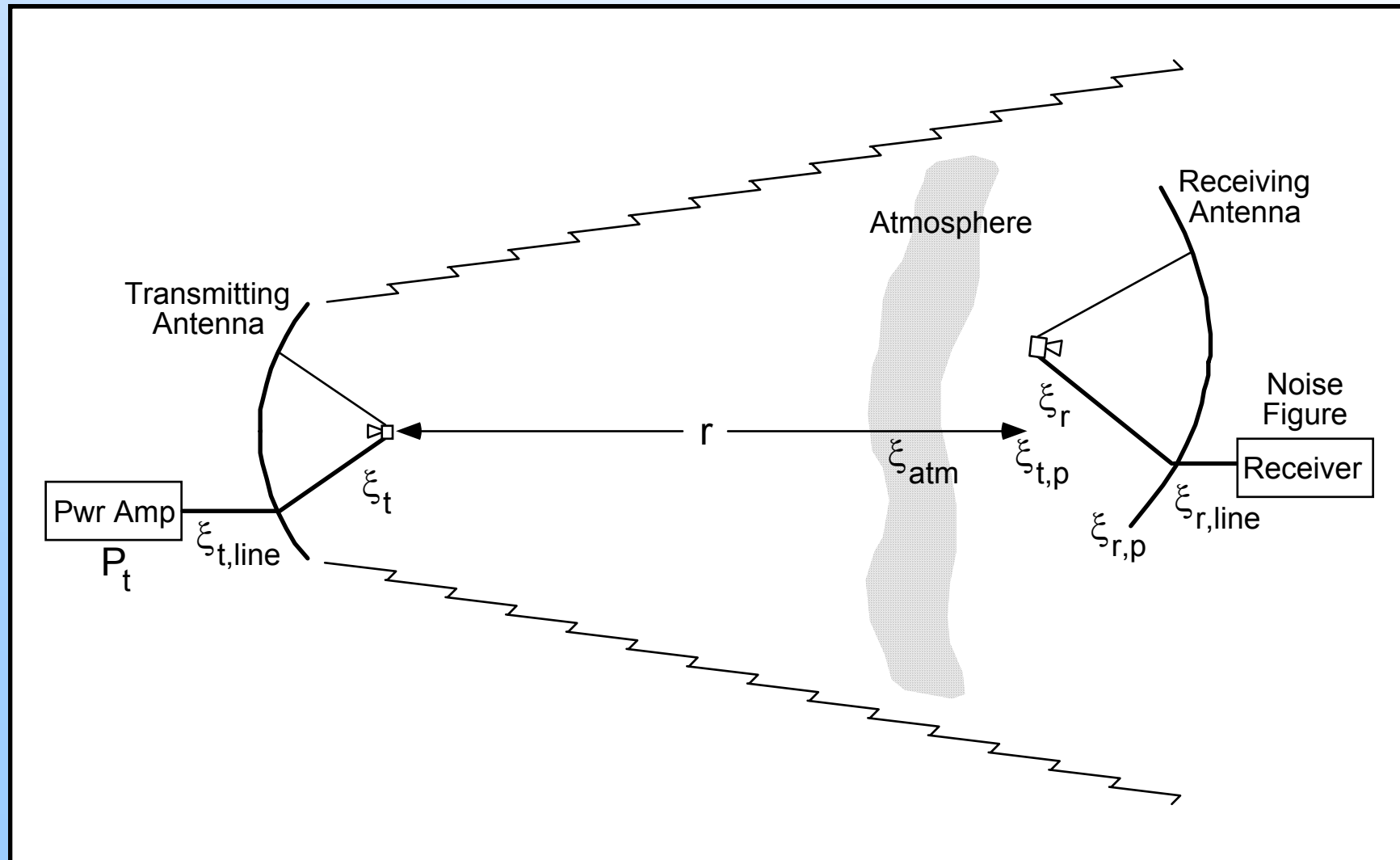


- A probe at some level within a planetary atmosphere ...
- ... must send a given volume of data in a given time (thus, at a known data rate) ...
- ... through the intervening atmosphere (and possibly other non-vacuum media) ...
- ... over some distance ...
- ... to a receiving station outside the atmosphere.
- How much does the atmosphere attenuate the data relay radio signal?



Knowing this is **critical** to designing a successful telecom system !





It all boils down to S/N!

- Approximation for a system's maximum data rate:

$$R_D \approx R_o \cdot \left( \frac{\pi}{4c} \right)^2 P_t \left( \frac{f D_t D_r}{r} \right)^2 \prod_i \xi_i$$

- or, equivalently:

$$R_D \approx R_o \cdot \frac{P_t}{16} \frac{G_t D_r^2}{r^2} \prod_i \xi_i$$

$P_t$ : transmitter power

$G_t$ : transmitting antenna *gain*

$D_r$ : receiving aperture diameter

$r$ : distance between antennas

$\xi$  : loss terms (e.g., signal absorption or scattering, antenna losses)

$R_o$ : constant (approximately) of proportionality depending on the receiving system's performance, coding schemes, noise, etc.

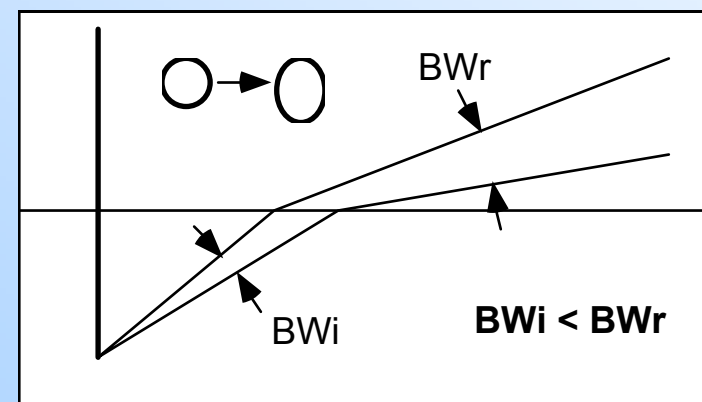
Distance  $r$  attenuates radio signals through “spherical divergence”

## Attenuation by Refractive Scattering

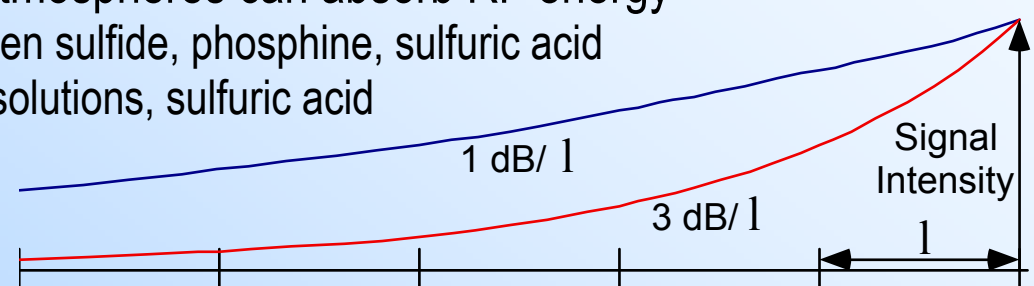
- Scattering changes the propagation direction of an EM wave
- Redirection of RF energy away from the antenna beam
- Due mostly to refractive inhomogeneities in atmospheres
  - Gases: Temperature variations, turbulence
  - Liquids: Cloud droplets and local concentrations
  - Solids: Ice cloud particles and local concentrations
- Can also occur in planetary and interplanetary plasmas

## Attenuation by Refractive Beam Spreading

- Bending of a refracted ray increases as the angle of incidence increases
  - “Bottom” of an antenna beam bends more than the “top”
  - Beam becomes elongated, spreads the energy over a larger area: attenuation
  - Important only at large zenith angles

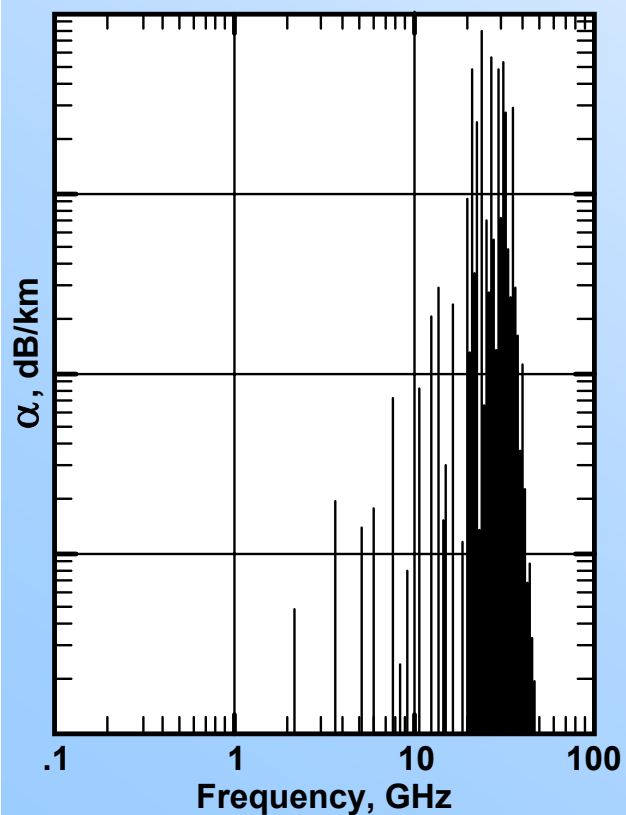


## Attenuation by Absorption

- Characterized by the *absorption coefficient*  $\alpha$ 
    - Units of Optical Depths or dB (some *logarithmic* unit) per unit length
    - Many influences: concentration of absorbers, T, P's of other gases, radio frequency
  - Many constituents of planetary atmospheres can absorb RF energy
    - Gases: ammonia, water, hydrogen sulfide, phosphine, sulfuric acid
    - Liquids: water, water-ammonia solutions, sulfuric acid
    - Solids: water, ammonia,  $\text{NH}_4\text{SH}$
    - Collisional plasmas
- 
- Absorption Spectrum: absorption coefficient vs (radio) frequency
    - Liquids: usually have non-resonant “Debye” spectra
      - ♦ Absorption coefficient of a given sample is proportional to  $f^2$
    - Polar gases (permanent dipole moment): very complex behavior, especially ammonia
      - ♦ Discrete transitions within coupled rotational-vibrational states (and other transitions) generate many absorption lines in the microwave through sub-mm-wave range
      - ♦ Pressure broadening increases line widths so they overlap, creating a continuum spectrum
      - ♦ Extreme pressure broadening produces a quasi-Debye spectrum, and can broaden powerful IR absorption lines into the RF portion of the spectrum
    - Non-polar gases: Only collision-induced dipole moment, weak Debye spectrum ( $\text{CO}_2$ ,  $\text{H}_2$ )

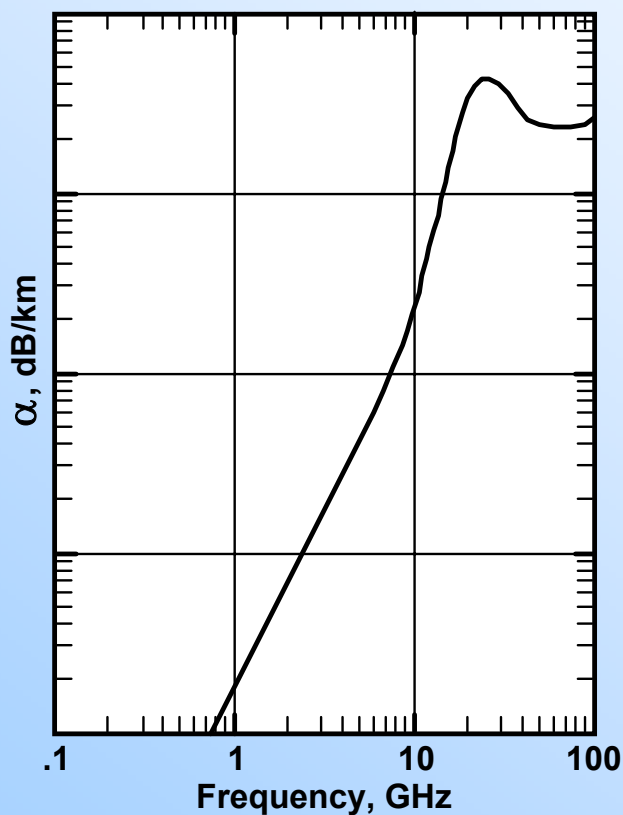
## Attenuation by Absorption in a Gas: Ammonia

Line spectrum



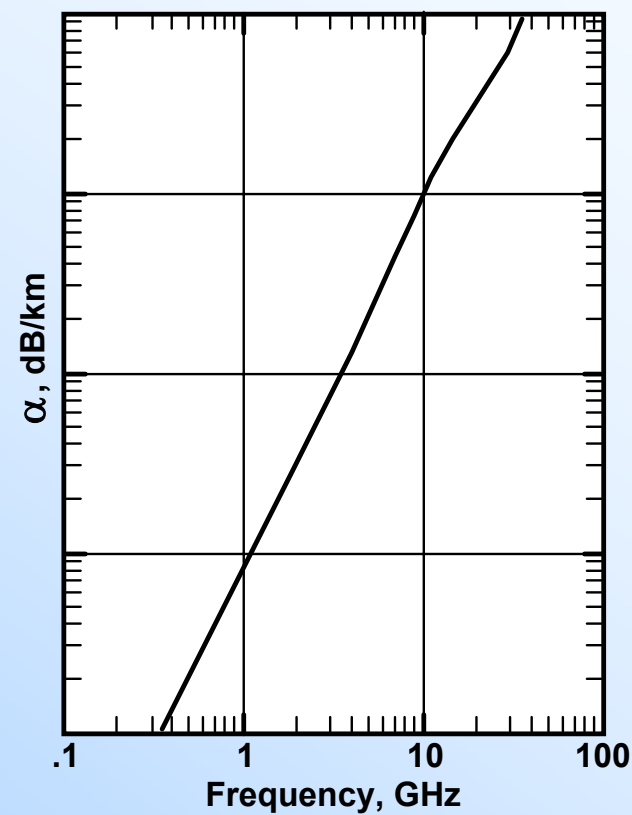
Few mb pure  $\text{NH}_3$

Pressure broadened



+ ~1 bar  $\text{H}_2$  + He

Near-Debye



+ 50-100 bars  $\text{H}_2$  + He



## Example Opacity Estimate: Jupiter

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- Telecom system engineers for JPL's "Team X" designed a probe data relay system for Jupiter deep probes
  - Designed for relay distance of ~200,000 km
  - PERFORMANCE:
    - ♦ It could maintain a data rate of 10 bits/s (minimum supportable) with up to

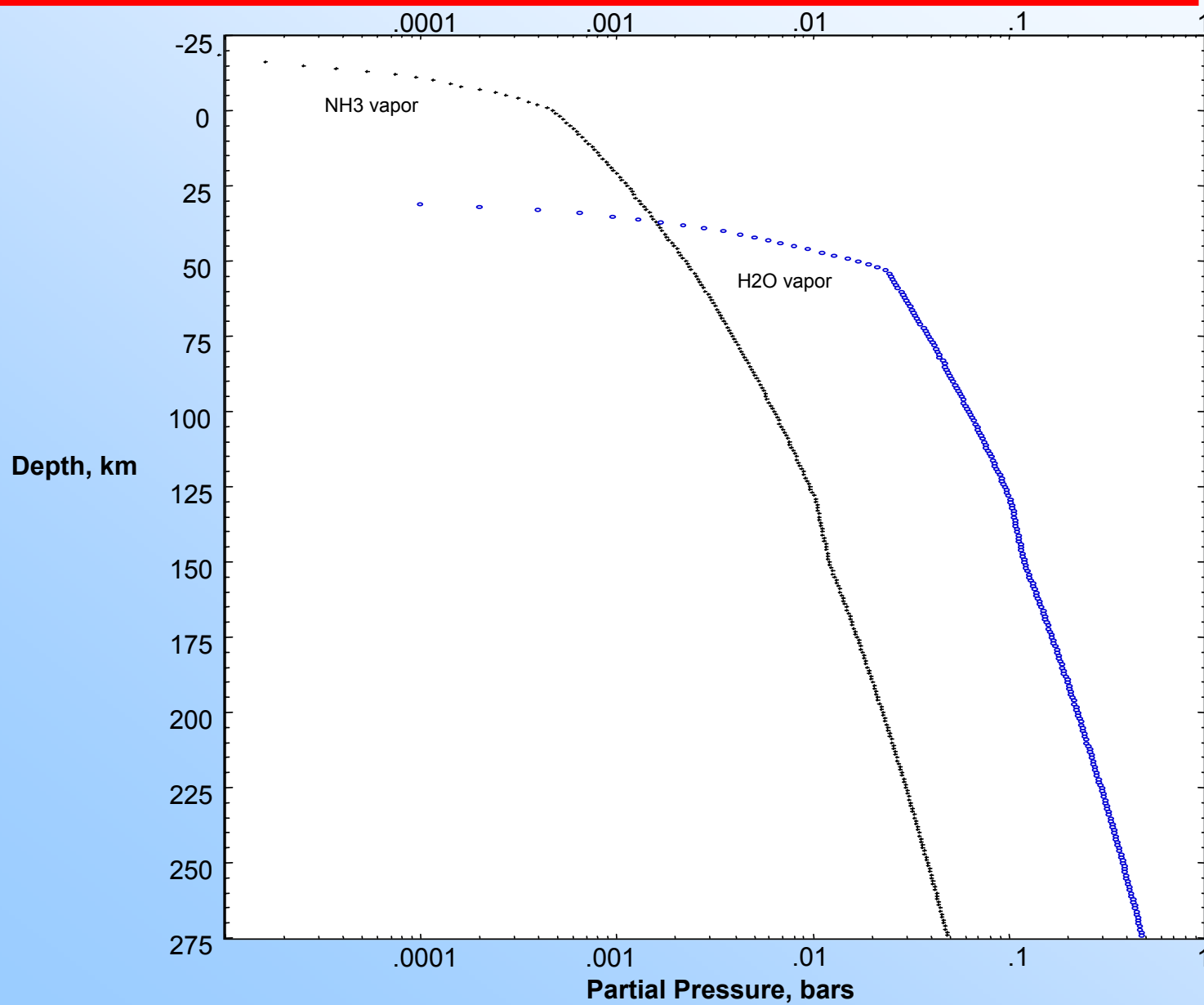
**24.5 dB**

of atmospheric attenuation

Question: How deep in Jupiter's atmosphere can it still maintain the link?



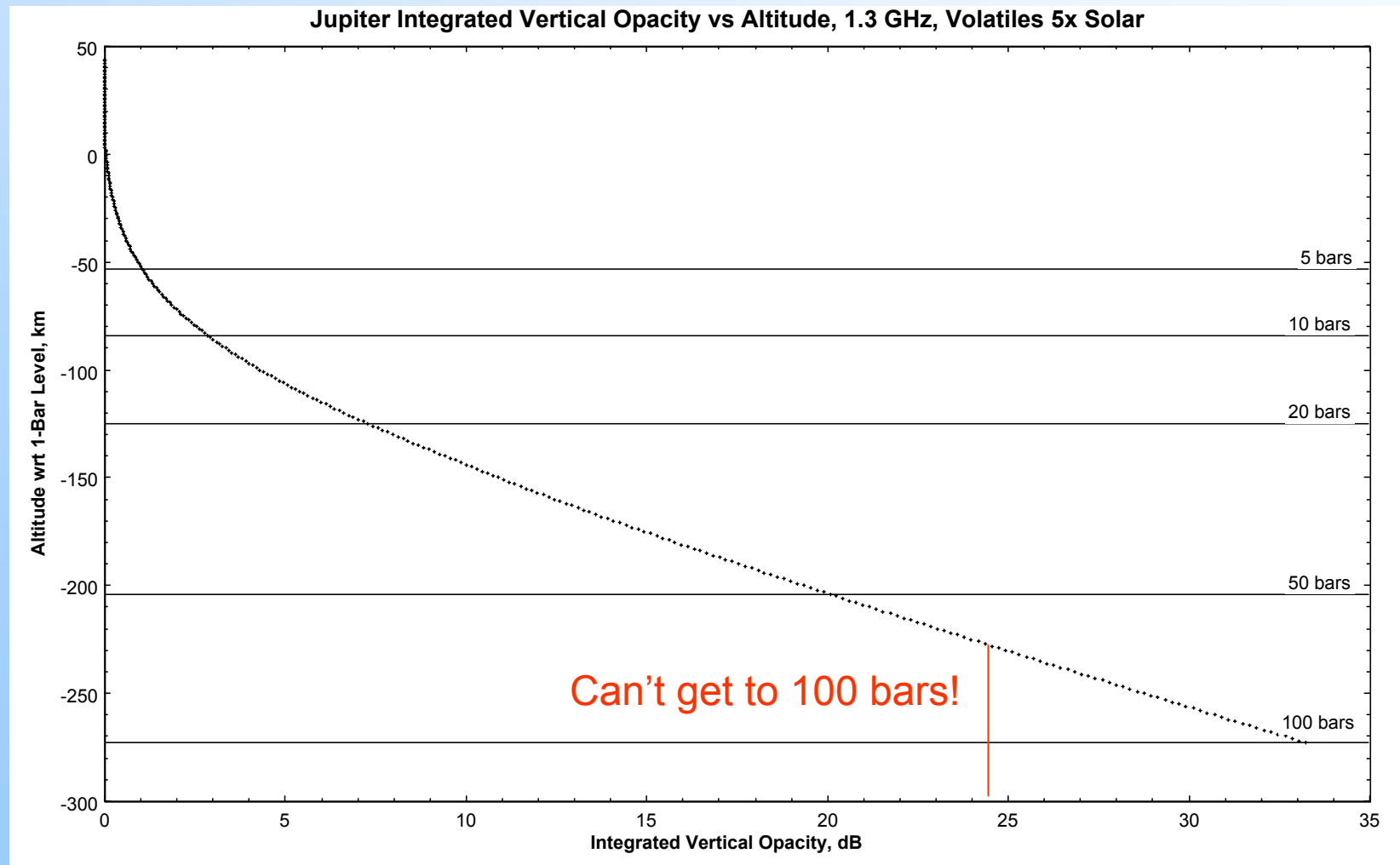
## Example Opacity Estimate: Jupiter







## Example Opacity Estimate: Jupiter





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Questions?